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Effects of solar wind dynamic pressure and preconditioning on large geomagnetic storms

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[1] We investigate the effects of solar wind dynamic pressure, P_{dyn}, and preconditioning in 88 large magnetic storms (Dst < −100 nT) occurring during solar cycle 23. We have developed an improved model of the Dst profile, based on a modified Burton equation, where additional effects of P_{dyn} and diminished Dst pressure-correction have been taking into account. On the average, our model predicts the Dst peak values within 9% of observations and gives an overall RMS error of 11%, which is an improvement over those models whose injection functions only depend on the solar wind electric field. The results demonstrate that there is an increase in the Dst peak value when there is a large enhancement of P_{dyn} during the main phase of a storm. The average increase of the storm intensity is estimated to be 26% for 15 storms with the max (P_{dyn}) > 15 nPa. We find that the preconditioning in multi-step Dst storms plays no significant role in strengthening the storm intensity, but increases the storm duration. **Citation:** Xie, H., N. Gopalswamy, O. C. St. Cyr, and S. Yashiro (2008), Effects of solar wind dynamic pressure and preconditioning on large geomagnetic storms, *Geophys. Res. Lett.*, *35*, L06S08, doi:10.1029/2007GL032298.

1. Introduction

[2] *Burton et al.* [1975] provided a simple equation (hereafter Burton equation) describing the dependence of the energy injection into the ring current system as a function of the solar wind electric field, indicating that the rate of change of Dst is proportional to the solar wind duskward electric field E_y. Using an empirical model, *O'Brien and McPherron* [2000] found that the decay time of the ring current in hours varies as $\tau = 2.4e^{9.74/(4.69+Ey)}$. The model of *O'Brien and McPherron* [2000] was improved to incorporate the diminished Dst pressure correction effect [*McPherron and O'Brien*, 2001] and Dst seasonal and diurnal variation [*O'Brien and McPherron*, 2002]. Furthermore, *Fenrich and Luhmann* [1998] and *Wang et al.* [2003] suggested that the Burton equation can be improved by including the influence of solar wind dynamic pressure, P_{dyn}.

[3] Burton empirical equation has had remarkable success in predicting the strength of geomagnetic storms [e.g., *Gonzalez et al.*, 1999]. However, the energy injection in the Burton equation and its variations depend only on the solar wind electric field and do not take into account the influence of P_{dyn} or any preexisting conditions in the magnetosphere. Thus they may not be applicable for large geomagnetic storms, in which various interplanetary magnetic field (IMF) structures are present along with large enhancements of P_{dyn}.

[4] In this work, we analyze 88 Coordinated Data Analysis Workshop (CDAW) large geomagnetic storms (Dst < −100 nT) during solar cycle 23. We study the effects of P_{dyn} and preconditioning in multi-step Dst storms [e.g., *Kamide et al.*, 1998; *Xie et al.*, 2006]. We include the influence of P_{dyn} to obtain an improved model for modeling the Dst index of large storms (section 2). The effect of preconditioning on multi-step Dst storms is investigated in section 3. Finally, we summarize our findings in section 4.

2. Effect of Solar Wind Dynamic Pressure on the Injection of the Ring Current

[5] The Burton equation has the form [*Burton et al.*, 1975]:

$$dDst^*/dt = Q(t) - Dst^*/\tau \tag{1}$$

$$Dst^* = Dst - b\sqrt{P_{dyn}} + c \tag{2}$$

where Dst^* is the pressure-corrected Dst index and the contribution of the magnetopause current has been removed in (2). The constant b is a measure of the pressure correction and c is a measure of the quiet-time ring current, magnetopause current, and magnetotail current. $Q(t)$ is the ring current injection term which depends only on the dawn-dusk solar wind electric field, $E_y = VB_s$, where V is the solar wind flow velocity and B_s is the interplanetary magnetic field (IMF) southward component. The constants b and c were determined by the quiet time slope $d(Dst)/d(P^{1/2})$ and the H-component of the quiet time ring current H_{rc}^q as $b = 15.8 \pm 7.9$ nT/(nPa)$^{1/2}$ and $c = 20$ nT. The ring current decay time, τ, is usually taken as 7.7 hours.

[6] To improve the fitting of the Dst index for large geomagnetic storms, three modifications to the Burton equation have been made in this study. First, the injection function has been modified to be $Q(t) \sim (E_y - E_c)(P_{dyn})^{0.5}$, which has a similar dependence on P_{dyn} as the saturated transpolar potential [*Siscoe et al.*, 2002a]. *Siscoe et al.* [2002a] applied the polar cap saturation model of *Hill et al.* [1976] which is based on the Vasyliunas scaling relations [*Vasyliunas et al.*, 1982] and found that the theoretical transpolar potential $\Phi_{pc} \sim P_{dyn}^{1/3}$ and the simulated saturation $\Phi_S \sim P_{dyn}^{2/3}$. Also, *Lopez et al.* [2004] performed global MHD simulations and indicated that solar wind density enhancement can increase the bow shock compression ratio (thus

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Table 1. Summary of Modeling Errors of the MO, WCB, and XGSY Models

	$\Delta Dst_{\min}$, nT[a]	RMS error, nT	$\Delta Dst_{\min}/\lvert Dst_{mean}\rvert$[b]	$RMS/\lvert Dst_{mean}\rvert$
MO model	34.4	27.8	23%	19%
WCB model	28.2	18.6	19%	12%
XGSY model	14.0	15.9	9%	11%

[a]$\Delta Dst_{\min}$ is the difference of Dst minimum between predictions and observations.
[b]$|Dst_{mean}|$ is the absolute mean value of $Dst_{\min}$ over the modeled storms.

larger fraction of energy transfer) during periods of strong southward IMF.

[7] The second modification made is in τ. We use a two-component decay, namely main phase decay and recovery phase decay, whose timescales are obtained by *O'Brien and McPherron* [2000] and *Wang et al.* [2003], respectively, as shown in equation (5).

[8] As a third modification, we have added the diminished Dst pressure correction effect. *McPherron and O'Brien* [2001] and *Siscoe et al.* [2002b, 2005] found that during the main phase of storms, the magnetopause current will make less contribution to Dst correction as E_y increases.

[9] In our model we use a slightly different form for the coefficient b as given by *McPherron and O'Brien* [2001], whose parameters are determined by the following procedure.

[10] Rewriting equation (1) and (2) as

$$dDst/dt - Q(t) + Dst/\tau = b\left(dP^{1/2}/dt + P^{1/2}/\tau\right) \qquad (3)$$

where we ignore the small baseline offset term c/τ and correlate $dDst/dt - Q(t) + Dst/\tau$ against $(dP^{1/2}/dt + P^{1/2}/\tau)$ for each bin of constant VB_s. The slope of the best-fit line then determines b as a function of VB_s, which is fitted with an exponential form. The constant c is defined as the Dst value at which ΔDst is zero during quiet days.

[11] All the equations used in this study are summarized as follows:

$$Q = \begin{cases} -4.4(VB_s - 0.49)\left(P_{dyn}/3\right)^{0.5}, & VB_s > 0.49 \text{ mV/m} \\ 0, & VB_s \le 0.49 \text{ mV/m} \end{cases} \qquad (4)$$

$$\tau = \begin{cases} 2.40e^{9.74/(4.69+VB_s)}, & B_z < 0 \\ -8.7e^{6.66/\left(6.04+P_{dyn}\right)}, & B_z \ge 0 \end{cases} \qquad (5)$$

$$b = 4.2 + 3.5e^{-VB_s}, \quad c = 10.8 \text{ nT} \qquad (6)$$

[12] We modeled the 88 CDAW large storms using solar wind, IMF, and Dst hourly data from the OMNI database of the National Space Science Data Center (http://omniweb.gsfc.nasa.gov/form/dx1.html). We solved the Dst differential equation using a Runge-Kunta algorithm by interpolating the hourly data to 10-minute intervals using the Aitken method to improve the accuracy of the solution. In order to compare our results to those from previous models, we used three models to fit the Dst profile: the model of *McPherron and O'Brien* [2001] (hereinafter referred to as the MO model), the model of *Wang et al.* [2003] (hereinafter referred to as the WCB model), and our model (hereinafter referred to as the XGSY model). The three models have similar forms of injection functions and decay times. They differ mainly in that the power index, γ, in our model is 0.5, while in the MO and WCB models, γ, are 0 and 0.2, respectively.

[13] Table 1 summarizes $\Delta Dst_{\min}$, RMS error, and the percentage errors of three models. Here $\Delta Dst_{\min}$ is the difference of Dst minimum between predictions and observations and the percentage error is respective to the mean $Dst_{\min}$ of the modeled storms. With the modifications discussed above, our model provides the best prediction with a mean $\Delta Dst_{\min}$ (percentage) error of 14 nT (~9%) and a mean RMS (percentage) error of 15.9 nT (~11%).

[14] Figure 1 plots the solar wind electric field, dynamic pressure, Dst predictions, and Dst measurements for the 31 March 2001 storm. The 31 March 2001 storm was a very intense storm ($Dst_{\min}$ = −387 nT) and had a maximum pressure $P_{\max}$ = ~40 nPa, caused by three successive CMEs, which were possibly interacting among themselves [c.f. *Xie et al.*, 2006].

[15] From Figure 1, we see that both the MO and WCB models underestimate the Dst peak value. Errors in Dst minimum ($\Delta Dst_{\min}$) for the MO and WCB models are 106 nT and 80 nT, respectively, and the percentage errors $\Delta Dst_{\min}/|Dst_{\min}|$ are 27% and 21%. By adding the influence

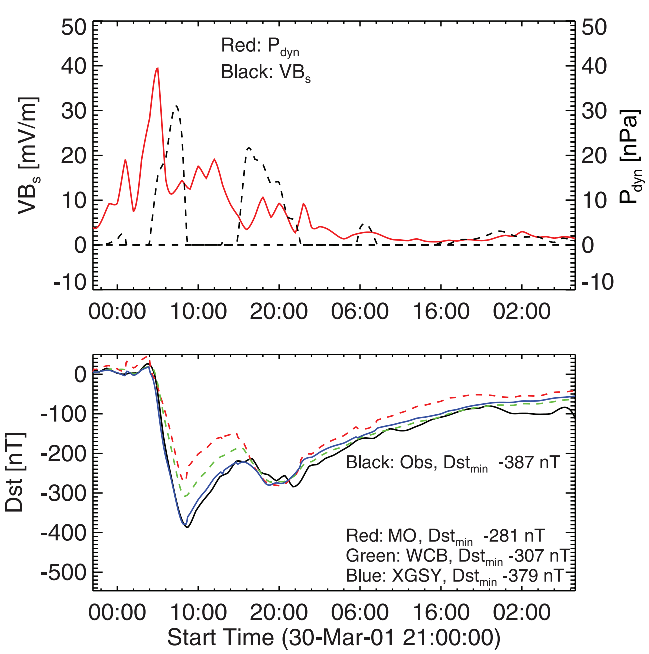

Figure 1. Solar wind and Dst parameters for an intense storm on March 31, 2001. Black, red, green, and blue curves represent the measured Dst and the modeled Dst from the MO model, the WCB model, and our model, respectively.

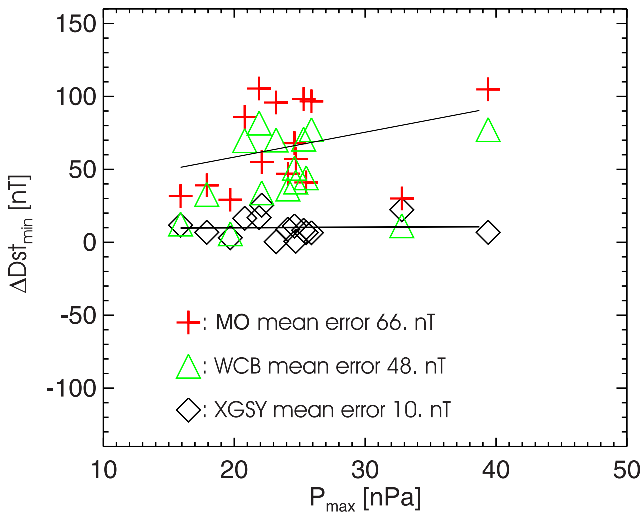

Figure 2. The error, $\Delta Dst_{\min}$, as a function of P_{dyn}. Cross, diamond, and triangle symbols represent the fitting errors from the MO, WCB, and our model, respectively. The solid lines show the linear fit to the MO and XGSY model's error.

of P_{dyn} with $\gamma = 0.5$, our model provides the best prediction with $\Delta Dst_{\min} = 8$ nT and $\Delta Dst_{\min}/|Dst_{\min}| = 2\%$.

[16] Figure 2 shows the error $\Delta Dst_{\min}$ of the three models as a function of P_{dyn} for 15 large storms with $P_{\max} > 15$ nPa. The results show that the error $\Delta Dst_{\min}$ for the MO and WCB models increases as $P_{\max}$ increases, and their mean values of $\Delta Dst_{\min}$ are 66 nT (~31%) and 48 nT (~23%), respectively. Our model ($\gamma = 0.5$) predicts the Dst peak values with a mean error of 10 nT (~5%), which is a significant improvement over the MO and WCB models. Compared with the MO model, our model results in an average increase of ~26% in the storm intensity due to the enhancement of P_{dyn}. The WCB model ($\gamma = 0.2$) results in a better prediction than the MO model does, although it does not fully account for the influence of P_{dyn}.

[17] Recently, *Temerin and Li* [2006] updated the previous *Temerin and Li* [2002] prediction model to data from 2000–2002. The *Temerin and Li* [2006] model predict the Dst quite well, even for large storms, with an overall RMS error of 6.65 nT. Comparing with *Temerin and Li*'s [2006] model, our model has a slight larger RMS of 15.9 nT. However, the *Temerin and Li*'s [2006] model includes a complex set (~10) of free parameters whereas ours is rather simple. As the authors point out there might be an offset among the effects of various parameters in the model, whereas our model provides a better physical insight.

3. Preconditioning in Large-Intensity Storms

[18] During large geomagnetic storms, multi-step Dst development often occurs in the main and recovery phases [e.g., *Xie et al.*, 2006], where multi-step storms are defined as those that consist of more than two Dst dips in the Dst profile, in a similar way as given by *Kamide et al.* [1998]. Figure 3 shows a multi-step Dst storm on August 27 1998, which has three Dst dips caused by different B_s in the sheath region and ICMEs (note: the fourth dip in the recovery phase is due to the fluctuation of P_{dyn}). The first Dst dip gives a preconditioning of −50 nT and the second dip gives a preexisting Dst of −140 nT. To examine the effect of preexisting ring currents on subsequent ring current intensifications, we conducted three model runs for this event: (1) including all three injections (blue curve); (2) with the first injection removed (green curve); (3) with both the first and the second injections removed (red curve).

[19] For the case without the first injection, the Dst reaches the level of dip 1 ($Dst_{\min} = -50$ nT) in a very short time (~10 mins). Almost the full value of dip 2 (98%) was reproduced. Without the two injections the Dst peak produced 88% of dip 3 value but its peak time has a ~6-hour delay, resulting in a reduced-duration storm. The preconditioning of injection 1 and injection 2 prolong the total duration of the storm substantially but causes only a small increase (~12%) in the total intensity of the storm. The above result can be understood from the Burton equation, since the loss term in (1) is proportional to Dst, more preconditioning leads to more loss in Dst. Furthermore, during the main phase, the decay time value asymptotes to 2.4 hr for large E_y, which is such a short decay time that it will rapidly sweep out all pre-storm ring current [c.f. *Liemohn et al.*, 1999]. Similar results has been obtained by previous ring current modeling studies [e.g., *Chen et al.*,

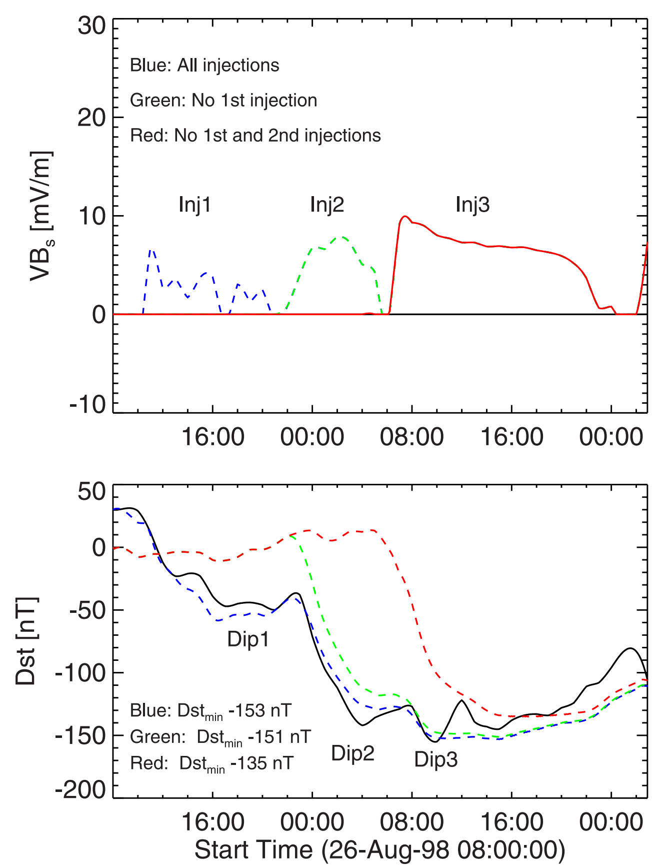

Figure 3. Solar wind dawn-dusk electric field, VB_s, for a three-step Dst storm on August 27, 1998. (top) Blue, green, and red curves denote three ring current injection intervals: injection 1, injection 2, and injection 3, respectively. (bottom) The measured Dst (black curve) and the modeled Dst: including all of the injection intervals (blue curve), only the second and the third injections (green curve), and only the third injection (red curve).

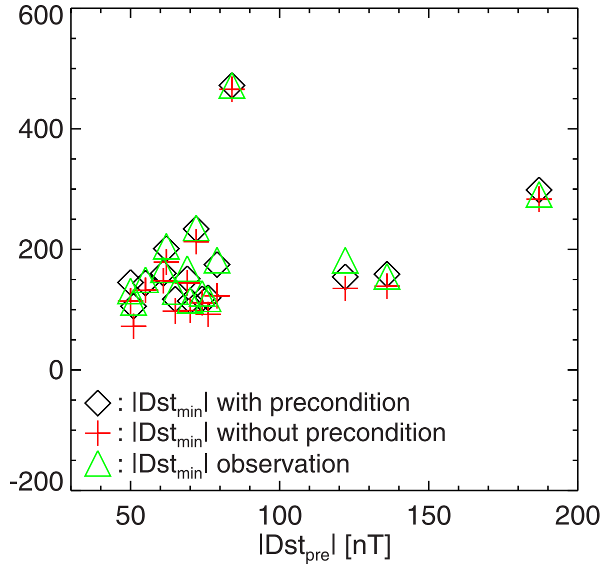

Figure 4. $|Dst_{\min}|$, absolute value of Dst minimum with (diamond) and without (cross) preconditioning, as a function of the absolute value of Dst preconditioning, $|Dst_{pre}|$, for 16 multi-step Dst storms. The observed $|Dst_{\min}|$ (triangle) are plotted as a reference in the figure.

2000; *Kozyra et al.*, 1998, 2002]. *Kozyra et al.* [2002] showed a very similar result to Figure 3, where the early injections of a multi-step storm on 4–6 June 1991 were removed from the model simulation. Although our empirical model is rather different from the ring current model of *Kozyra et al.* [2002], where the kinetic equations of the ring current particles for the Phase-space distribution function are solved in the inner magnetosphere, almost identical results are obtained.

[20] To further investigate the effect of preconditioning in large geomagnetic storms, we analyzed 16 multi-step Dst events. Let $|Dst_{\min}|$ be the absolute value of Dst peak and $|Dst_{pre}|$ be the absolute value of Dst preconditioning, Figure 4 shows $|Dst_{\min}|$ with (diamond) and without (cross) preconditioning as a function of $|Dst_{pre}|$ for the 16 multi-step Dst storms. The obtained $\Delta|Dst_{\min}|$ between the Dst peak with and without preconditioning varies in a small range from 0.4 nT to 45 nT, and the mean value of $\Delta|Dst_{\min}/Dst_{pre}|$ is ~24%, i.e., with a preconditioning of −100 nT the average $\Delta Dst_{\min} = -24$ nT. The result shows that preconditioning in multi-step Dst storms does not play a significant role in strengthening the storm intensity in general.

4. Summary and Conclusions

[21] We have analyzed 88 large geomagnetic storms ($Dst < -100$ nT) of solar cycle 23 to investigate the effects of the solar wind dynamic pressure and preconditioning in multi-step Dst storms using a modified Burton equation. The main findings are:

[22] 1. The strength of large storms is proportional to the product of the duskward electric field and dynamic pressure of the solar wind $Q \sim E_y(P_{dyn})^{0.5}$. The average increase in the storm intensity is estimated to be 26% for the 15 storms with the maximum $P_{dyn} > 15$ nPa.

[23] 2. By taking into account the additional effect of P_{dyn} and diminished pressure correction to Dst, our model predicts the Dst peak values within 14 nT (9%) of observations, which is a significant improvement over the MO and WCB models. The mean values of $\Delta Dst_{\min}$ error for the three models are 34.4 nT (MO model), 28.2 nT (WCB model), and 14 nT (XGSY model), and their percentage errors are 23%, 19%, 9%, respectively.

[24] 3. Preconditioning of preexisting ring currents does not play a significant role in strengthening the storm intensity. Instead, such intensifications (with a similar magnitude as the major one) can prolong the storm duration.

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